



84

INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 5 : H01F 29/14		A1	(11) International Publication Number: WO 94/11891 (43) International Publication Date: 26 May 1994 (26.05.94)
(21) International Application Number: PCT/SE93/00946			(74) Agent: LUNDBLAD VANNESJÖ, Katarina; ABB Corporate Research, Patent Department, S-721 78 Västerås (SE).
(22) International Filing Date: 9 November 1993 (09.11.93)			(81) Designated States: CA, JP, US, European patent (AT, BE, CH, DE, DK, ES, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE).
(30) Priority data: 9203331-5 9 November 1992 (09.11.92) SE			Published <i>With international search report. In English translation (filed in Swedish).</i>
<p>(71) Applicant (<i>for all designated States except US</i>): ASEA BROWN BOVERI AB [SE/SE]; S-721 83 Västerås (SE).</p> <p>(72) Inventors; and</p> <p>(75) Inventors/Applicants (<i>for US only</i>) : VALDEMARSSON, Stefan [IS/SE]; Tomteboda, Gäddeholm, S-725 97 Västerås (SE). LILJESTRAND, Lars [SE/SE]; Björnramsvägen 12, S-722 42 Västerås (SE).</p>			
(54) Title: CONTROLLABLE INDUCTOR			
(57) Abstract			
<p>The invention relates to an inductor with variable inductance based on the principle of orthogonal magnetization, that is, control of the permeability of the magnetic material with the aid of a cross-directional control field. The inductor has a main winding (2) which is intended for alternating current and which surrounds a tubular core (3) wound from tape-formed magnetic material. The core is composed of a plurality of ring cores (31) which are stacked coaxially one above the other and which are axially divided and angularly displaced relative to each other. Axially through the core extends a control winding (4) intended for direct current. By changing the current in the control winding, the permeability of the core is changed in its axial direction and hence also the inductance of the inductor. The eddy-current losses in the core can be considerably reduced by making the core conically tapering towards its ends or by arranging so-called flux funnels (8) with radially bladed laminations near the ends of the core. The inductor is especially suitable for use in power plants, for example in tunable harmonic filters for high-voltage direct current.</p>			

FOR THE PURPOSES OF INFORMATION ONLY

Codes used to identify States party to the PCT on the front pages of pamphlets publishing international applications under the PCT.

AT	Austria	GB	United Kingdom	MR	Mauritania
AU	Australia	GE	Georgia	MW	Malawi
BB	Barbados	CN	Guinea	NE	Niger
BE	Belgium	CR	Greece	NL	Netherlands
BF	Burkina Faso	HU	Hungary	NO	Norway
BG	Bulgaria	IE	Ireland	NZ	New Zealand
BJ	Benin	IT	Italy	PL	Poland
BR	Brazil	JP	Japan	PT	Portugal
BY	Belarus	KE	Kenya	RO	Romania
CA	Canada	KG	Kyrgyzstan	RU	Russian Federation
CF	Central African Republic	KP	Democratic People's Republic of Korea	SD	Sudan
CG	Congo	KR	Republic of Korea	SE	Sweden
CH	Switzerland	KZ	Kazakhstan	SI	Slovenia
CI	Côte d'Ivoire	LI	Liechtenstein	SK	Slovakia
CM	Cameroon	LK	Sri Lanka	SN	Senegal
CN	China	LU	Luxembourg	TD	Chad
CS	Czechoslovakia	LV	Latvia	TC	Togo
CZ	Czech Republic	MC	Monaco	TJ	Tajikistan
DE	Germany	MD	Republic of Moldova	TT	Trinidad and Tobago
DK	Denmark	MG	Madagascar	UA	Ukraine
ES	Spain	ML	Mali	US	United States of America
FI	Finland	MN	Mongolia	UZ	Uzbekistan
FR	France			VN	Viet Nam
GA	Gabon				

Controllable inductor

TECHNICAL FIELD

5 The present invention relates to a variable inductor, that
is, a reactor with variable inductance, of the kind described
in the preamble to claim 1. The inductor has a main
winding intended for alternating current and surrounding at
least one elongated tubular core of magnetic material.
10 Through the axial channel of the tubular core extends a
control winding intended for direct current. Inductors of
this type, which have an open (i.e. not closed) core of
magnetic material, the permeability of which is controlled
with the aid of a transversely directed control field, so-
15 called cross-magnetization, are particularly suitable for
use in tunable harmonic filters for both high-voltage direct
current and high-voltage alternating current, but also other
applications are feasible, for example in static reactive
power compensators.

20

BACKGROUND ART

○ Controllable inductors, in which the permeability of the
magnetic material of the inductor is controlled with the aid
25 of cross-magnetization, are previously known from, for
example, EP-C- 0 010 502 and SU-A- 678 542. These inductors
are designed with a closed iron core, of which, however,
only a small part is influenced by the control field gene-
rated by the d.c. winding. This results in poor utilization
30 of the number of ampere turns of the a.c. winding, since a
reduction of the hysteresis losses and the permeability of
the core, which is of importance for the energy storage
capacity, is achieved only in that part of the core which is
being influenced by both the alternating and the direct
35 field. This means that the known inductors are heavy and
bulky in relation to their energy storage capacity.
Furthermore, in prior art designs the magnetic cores are
sometimes designed such that "sly paths" for the alternating

flux are created, which may, inter alia, result in distortion in the a.c. curve because of superposition of the direct field.

5 From DE-C-911 293 an inductor which is controllable by cross-magnetization is previously known, the inductor being provided with a hollow cylindrical open core, through which the control winding passes. For the purpose of reducing the eddy-current losses, the core is designed with conically 10 tapering end portions. To be able to achieve a sufficiently strong cross-magnetization using a moderate control current, the control winding must be designed with a large number of turns. This entails difficulties in the manufacture since, for each turn, the winding wire must be drawn through the 15 axial hole of the core, which hole is relatively elongated and has a limited cross section.

SUMMARY OF THE INVENTION

20 The object of the invention is to provide a controllable inductor intended for the above purpose, which makes possible a high energy density, has low iron losses, and exhibits a linear ratio of the current to the voltage. As far as the above-mentioned application to tunable harmonic 25 filters for HVDC is concerned, on the other hand, the demands for the maximum inductance variation of the inductor are relatively moderate, for example $\pm 10\%$. In addition, it shall be possible to manufacture the inductor in a relatively simple way. An inductor with these properties is 30 achieved according to the invention with a design which has the characteristic features described in claim 1.

By composing the iron core of the inductor from several ring-cores stacked one above the other and being axially 35 divided, the core can be mounted around a control winding which has been wound in advance. This greatly facilitates the manufacture of the inductor. In spite of the fact that the ring-cores are axially divided, a core with a high

mechanical stability can be obtained by angularly displacing the parting planes of adjoining ring-cores relative to each other.

5 According to a further development of the invention, the stability of the core can be further improved by designing the ring-cores funnel-shaped. This results in the ring-cores being automatically centred during mounting, and because the axial parting planes of adjoining ring-cores are angularly
10 displaced relative to each other, the ring-cores are prevented from moving in relation to each other. By displacing the winding turns axially, during the winding of the cores, for achieving the funnel-like shape, the additional advantage is obtained that the risk of turns being subjected to a short
15 circuit owing to burrs on the sheet tapes is reduced, which entails reduced eddy-current losses.

In an inductor according to the invention, the entire core will be under the influence of the cross-directional control field generated by the d.c. winding. This means that all the material in the core can be efficiently utilized for storage of magnetic energy. The reason is that the reactive power density (VA/kg) is inversely proportional to the relative permeability of the core material. By maintaining a high
25 field strength (A/m) in the control field, a low permeability in the longitudinal direction of the core and hence a very high power density can be obtained; for example, in a control field of 10^5 A/m a power density of about 1000 VA/kg can be obtained at 50 Hz. Higher frequencies give proportionally higher power density. An additional advantage of a
30 high control field strength is that the hysteresis losses in the core are practically eliminated.

With regard to the eddy-current losses, these can be considerably reduced according to the invention by making the core conically tapering towards its two ends, and preferably such that the conicity increases in a direction towards the ends. In this way, the alternating flux generated by the

main winding of the inductor may become axially directed, such that the field lines follow the sheet direction in the whole length of the core.

- 5 According to an alternative embodiment of the invention, the eddy-current losses can be reduced by arranging stacks of sheets, so-called flux funnels, near the ends of the core, the laminations of which are directed perpendicular to the end surfaces of the core and substantially radially in
10 relation to the centre line of the core.

In an inductor according to the invention, the inductance variation, that is, the dynamics, which is achieved by changing the direct current in the control winding, will
15 greatly depend on the length of the core in relation to its cross-section area and on the ratio of the area of the main winding to the area of the core. However, the dynamics will generally be low, but fully sufficient for the above-mentioned application in tunable harmonic filters for HVDC.

20

BRIEF DESCRIPTION OF THE DRAWINGS

The invention will be explained in greater detail by description of embodiments with reference to the accompanying
25 drawing, wherein

Figure 1 shows an axial section through an inductor designed according to the invention,

30 Figure 2 shows a cross section through the inductor along the line II-II in Figure 1.

Figure 3 shows a picture of the magnetic field at one end portion of the magnetic core of the inductor, produced by computer calculation,
35

Figure 4 shows curves of the relative permeability of an inductor core of mu-metal as a function of a longi-

tudinal alternating field at different values of a cross-magnetizing direct field.

Figure 5 shows an axial section through a second embodiment
5 of an inductor according to the invention,

Figure 6 shows an axial section through a third embodiment
of an inductor according to the invention,

10 Figure 7 shows in side view an iron core provided with a control winding and included in the inductor according to Figure 6, and

15 Figure 8 shows in axial section two of the ring-cores of the inductor core in an alternative embodiment.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

The inductor shown in Figures 1 and 2 has a main winding 2 which is wound around a tube 1 of insulating material and which coaxially surrounds a tubular iron core 3. The core is built up of a plurality of ring cores 31, stacked on top of each other, which are wound from sheet tapes the thickness of which may be, for example, 0.3 mm or smaller, depending 20 on the frequencies for which the inductor is intended and the eddy-current losses associated therewith. The core material may, for example, be oriented transformer sheet, amorphous sheet, mu-metal, etc. A number of the ring cores located nearest the ends of the core are conically turned 25 such that the core is continuously tapering towards the ends. Through the axial hole 32 of the core extends a control winding 4 divided into several coils. The mounting of this control winding is facilitated by dividing the ring cores 31 axially along a parting plane 33 (Fig. 2). The 30 halves of the ring cores are retained by surrounding straps of insulating material, and the whole core is compressed in the axial direction by a number of insulated clamp bolts 35 (not shown) which extend between two end rings 34, 35.

When a direct current I flows through the control winding 4, a circulating direct flux is generated in the ring cores, the permeability of the core in the axial direction thus being reduced. The main winding 2, which is connected into an a.c. circuit and generates an axially directed alternating flux in the iron core 3, will thus change its inductance when the control current I is changed.

The tapering of the iron core towards its ends is adapted such that the alternating flux inside each ring core becomes axially directed, that is, along the direction of the sheet. Radial flux inside the core material has thus become eliminated, whereby the eddy-current losses are reduced considerably and a high factor of merit (Q-value) for the inductor can be achieved. Figure 3 shows the magnetic field lines at one end portion of the inductor core 3 in an embodiment where the relative permeability of the core is $\mu_r = 30$. As is clear from the field picture, it is only in the very outermost part of the end portion that the field lines exhibit a radial directional component, which, however, because of the limited area, does not give rise to eddy-current losses of any practical importance.

Figure 4 shows how the relative permeability μ_r of a core of the shown kind, made of mu-metal, varies as a function of a longitudinal alternating field H_{ac} at different values of a transverse direct field H_{dc} varying between 0 and 42600 A/m.

The inductor shown in Figure 5 differs from that shown in Figure 1 in that it has two cores 3 of the shown kind arranged adjacent to each other, the control winding 4 passing through both of these cores. Since a greater part of the control winding is thereby surrounded by core material, the winding material is utilized in a better way, and it is sufficient with a lower control power.

Also the inductor shown in Figure 6 has two tubular cores 6 arranged adjacent to each other, through both of which the

- control winding 4 passes, as is clear from Figure 7. Each such core is built up of a number of ring cores, which are stacked on top of each other into a suitable length. For the control winding 4 to be manufactured and mounted in a simple way in the axial channels of the cores, the ring cores are divided into two halves along an axial parting plane. The ring cores are retained by surrounding straps and axial clamp bolts in the same way as described with reference to Figure 1. When a direct current flows in the control winding 4, a circulating magnetic direct field is generated in the tubular cores. By varying this field from $1-10^6$ A/m, the relative permeability in the longitudinal direction of the core may be changed from about 20000 to 2.
- 15 Figure 8 shows an alternative embodiment of the ring cores from which the iron core of the inductor is composed. The funnel-like shape of these cores can suitably be achieved by winding the sheet tape, of which the cores consist, on a cylindrical coil form which has a flange with a conical guide surface for the sheet tape. With ring cores of this design, the mounting of the inductor core is facilitated by the ring cores becoming self-centring and, in addition, fixed relative to each other, if the joint between the core halves is rotated through an angle of, for example, 10-90
- 20 degrees in relation to the preceding core. This makes the design more stable and less sensitive to mechanical stresses.
- 25 The core type shown in Figure 7, provided with its own d.c. winding, constitutes a core with a variable permeability, as described above. This core may constitute a construction part of its own, which may, for example, be built into an ordinary air coil to achieve a controllable inductor, for example of the design shown in Figure 6. The inductor according to Figure 6 has a main winding 2 which is wound on a plastic tube 1 and which surrounds the variable core 6, 4, which is provided with so-called flux funnels 8 at each end. When the permeability of the core is changed with the aid of

direct current in the control winding 4, the inductance of the coil 2 with the core 6 will vary.

- The task of the flux funnels 8 is to control the magnetic alternating flux in the longitudinal direction of the core. By designing the flux funnels with a relatively large air area, all the flux will leave the core via the funnels. The flux funnels consist of stacks of sheets, the laminations of which are perpendicular to the end surfaces of the core and are directed substantially radially in relation to the centre line of the core. The manufacture of these funnels may, for example, be performed in the manner described in SE-B- 324 404.
- Another possibility of controlling the magnetic flux in the longitudinal direction of the core is to arrange an eddy current-conducting shield around the core, or, alternatively, two shields around each of the end portions of the core. Such a shield can suitably be built up of a plurality of turns of a tape of electrically conducting material, for example copper or aluminium, wound one above the other, with an insulating film arranged at least on one side of the tape. The shield may, for example, have a thickness of 5 mm and be wound from 0.2 mm thick tape.
- The invention is not limited to the embodiments shown but several modifications are possible within the scope of the claims. In, for example, an embodiment where the ratio of the length of the iron core to the diameter thereof is considerably smaller than in the examples shown in Figures 1 and 5, it may be suitable to form the iron core with both an outside diameter decreasing towards the ends and an inside diameter increasing towards its ends.
- Further, it is not absolutely necessary that the current in the control winding be direct current, but in certain cases the control current may be alternating current as well.

As mentioned above, an inductor according to the invention is particularly suitable for use in harmonic filters in converter stations for high-voltage direct current (HVDC). In this way, these filters can be made controllable and the filter tuning continuously adjustable according to the operating conditions prevailing. This makes possible a reduction of the cost of construction of the whole HVDC station.

CLAIMS

1. A controllable inductor comprising at least one tubular core (3, 6) wound from tape-formed magnetic material and composed of a plurality of ring cores (31) stacked coaxially on top of each other, a main winding (2) which surrounds the core (3, 6), and a control winding (4) which passes axially through the core, wherein the two end portions of the core (3, 6) or any magnetic field-controlling members (8),
5 arranged near the end portions, are designed such that the magnetic flux in the core, generated by the main winding (2), is at least approximately axially directed in the length of the entire core, characterized in that the ring cores (31) are axially divided and arranged such that the
10 parting planes (33) of adjoining ring cores are angularly displaced relative to each other.
2. An inductor according to claim 1, characterized in that the ring cores (31) are funnel-shaped.
20
3. An inductor according to claim 1 or 2, characterized in that the angular displacement between the parting planes (33) of adjoining ring cores (31) is greater than 5 degrees.
25
4. An inductor according to claim 1, 2 or 3, characterized in that the core (3) is tapering towards its two ends.
30
5. An inductor according to claim 4, characterized in that the tapering of the iron core (3) towards the ends thereof is brought about by stacking ring cores of different diameters on top of each other.
35
6. An inductor according to claim 4, characterized in that the iron core (3) is conically tapering towards its two ends, preferably with increasing conicity in a direction towards the ends.

7. An inductor according to claim 6, characterized in that the tapering of the iron core (3) towards the ends thereof is brought about by turning.

5 8. An inductor according to claim 1, 2 or 3, characterized in that said magnetic field-controlling members (8) consist of stacks of sheet which are arranged axially outside and close to each one of the two end portions of the core (6), the laminations of the sheet stack being perpendicular to
10 the end surfaces of the core and being directed substantially radially in relation to the centre line of the core.

9. An inductor according to claim 1, 2 or 3, characterized in that said magnetic field-controlling members consist of
15 shield members which surround at least the end portions of the core and which consist of several turns of a tape of electrically conducting material, wound one above the other, with an insulating film arranged at least on one side of the tape.

20 10. An inductor according to any of the preceding claims, characterized in that it comprises two cores of said kind, arranged adjacent to each other, through which the control winding passes.

25 11. The use of a controllable inductor according to any of the preceding claims in a harmonic filter for high-voltage direct current or high-voltage alternating current.

FIG. 1

1/3

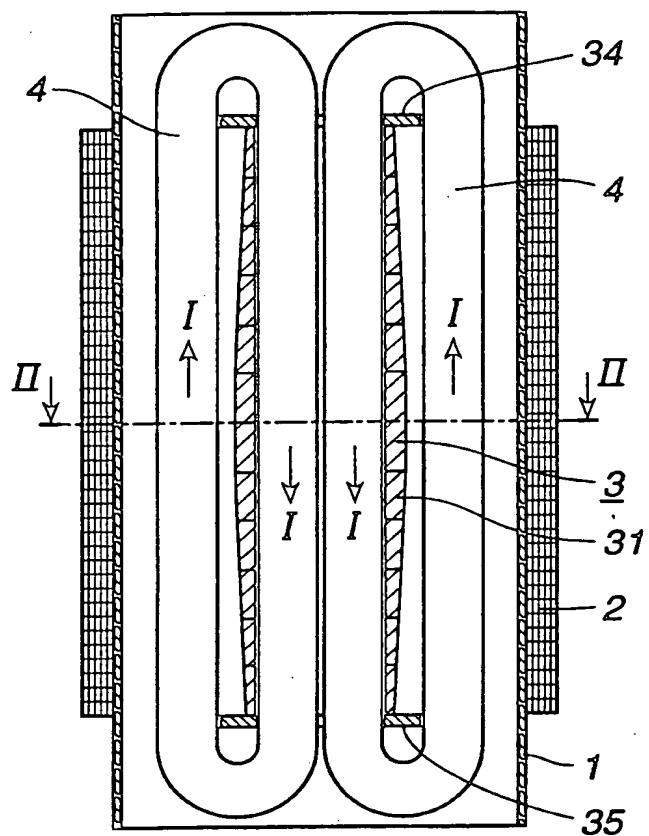


FIG. 5

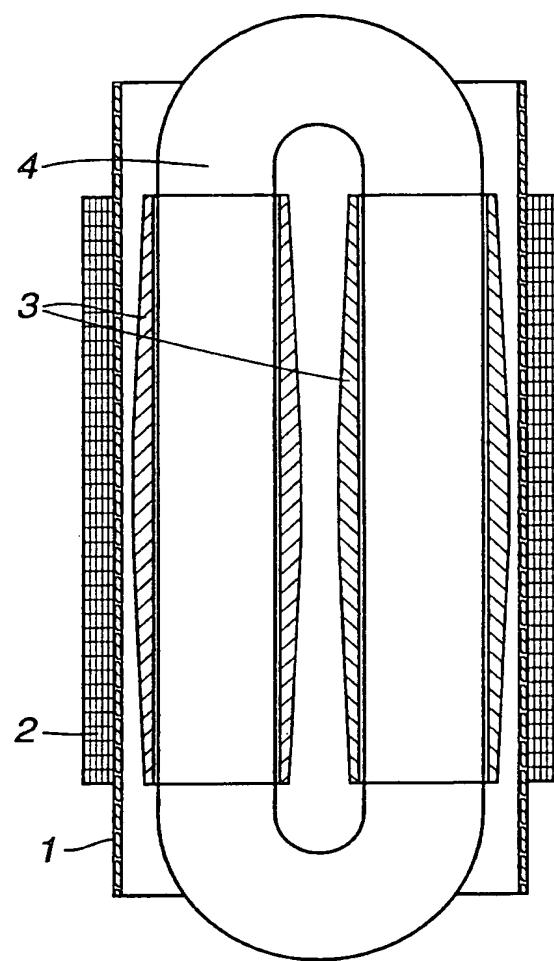


FIG. 2

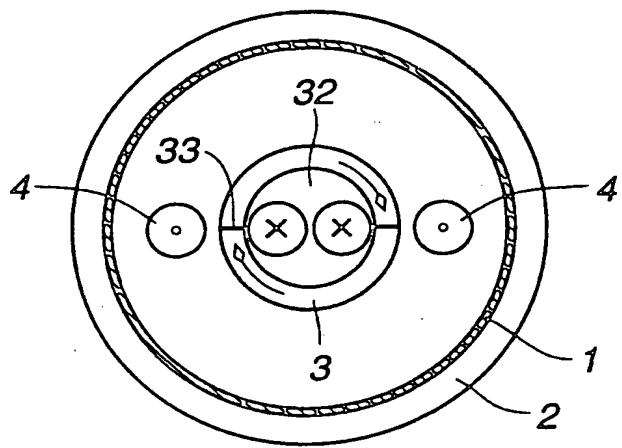


FIG. 3

2/3

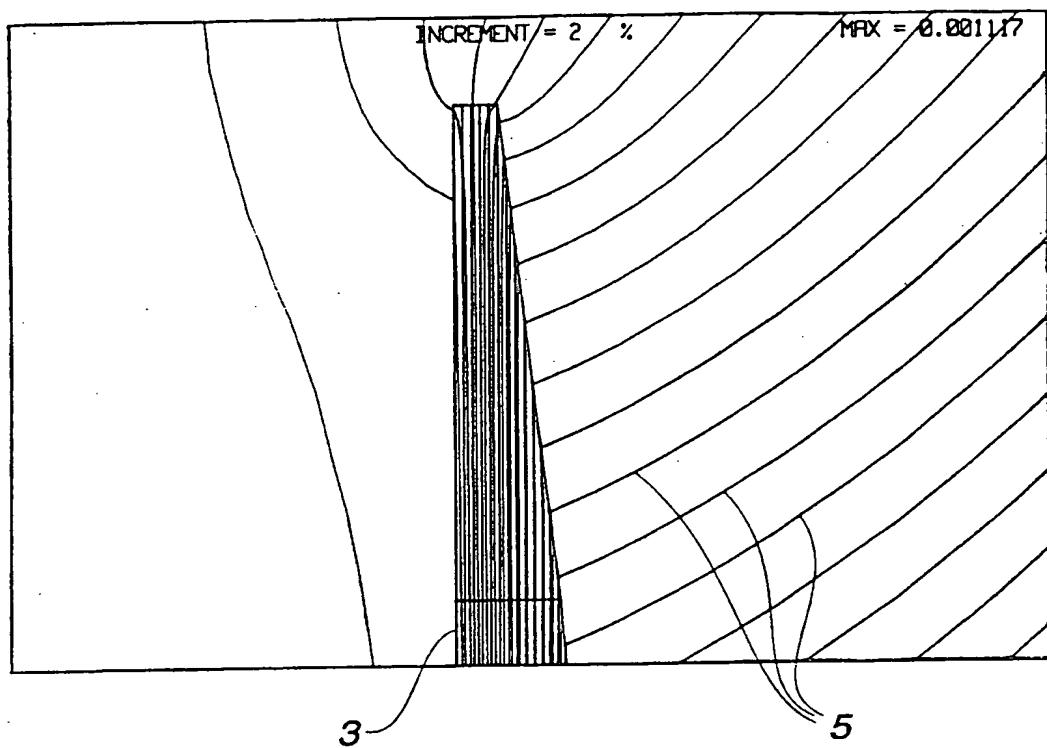


FIG. 4

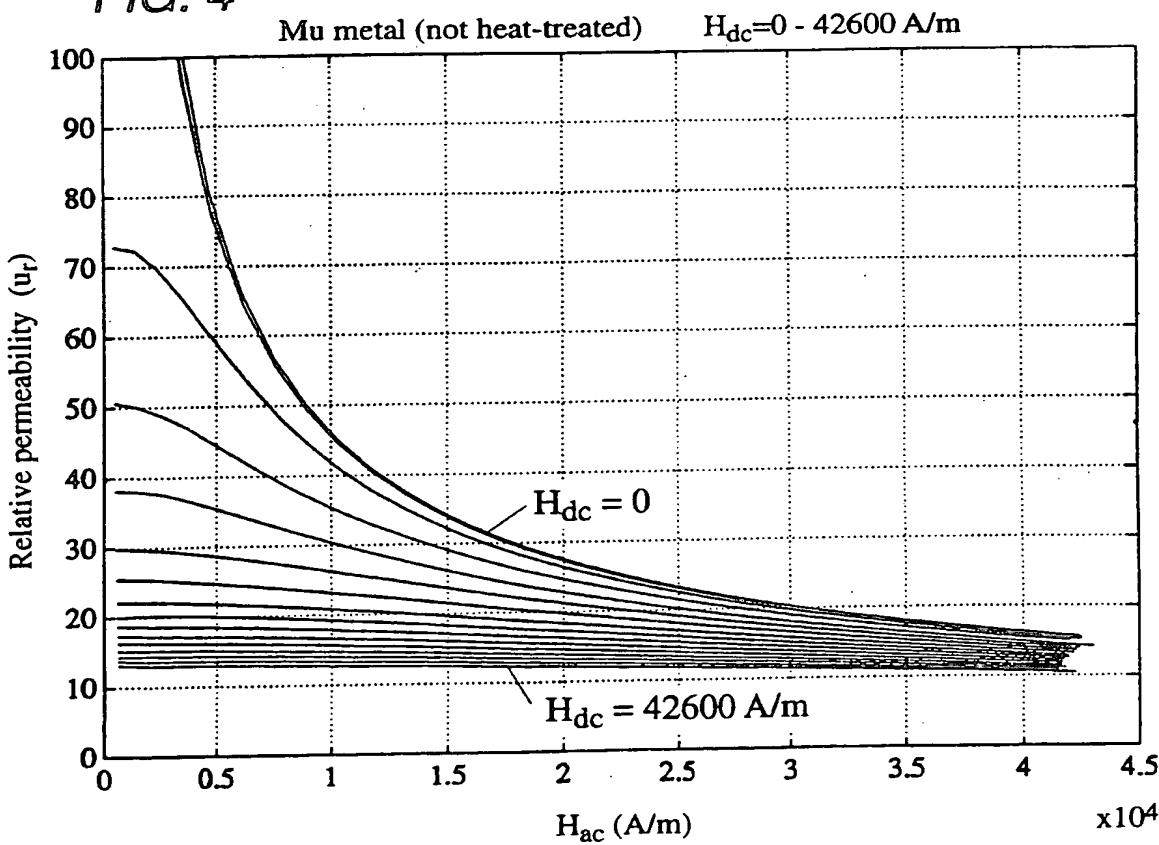


FIG. 6 3/3

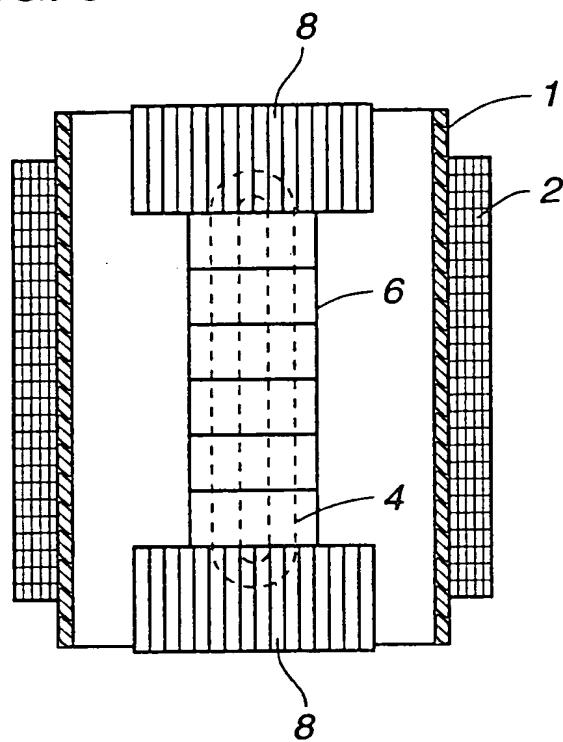


FIG. 7

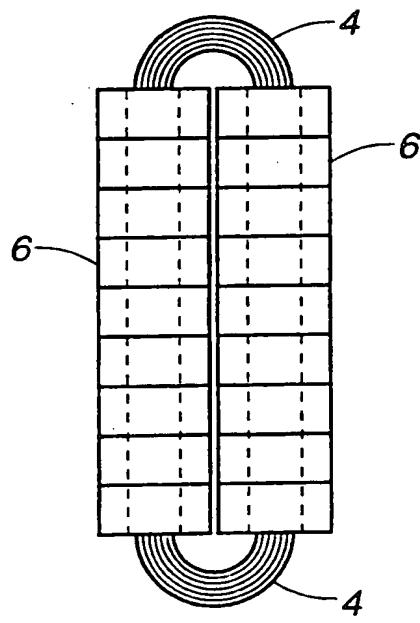
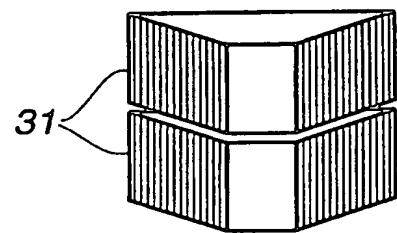


FIG. 8



INTERNATIONAL SEARCH REPORT

International application No.

PCT/SE 93/00946

A. CLASSIFICATION OF SUBJECT MATTER

IPC5: H01F 29/14

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC5: H01F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

SE,DK,FI,NO classes as above

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	DE, C1, 911293 (ALLGEMEINE ELEKTRICITÄTS-GESELLSCHAFT), 17 Sept 1953 (17.09.53) -----	1

 Further documents are listed in the continuation of Box C. See patent family annex.

- * Special categories of cited documents:
- "A" document defining the general state of the art which is not considered to be of particular relevance
- "B" earlier document but published on or after the international filing date
- "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
- "O" document referring to an oral disclosure, use, exhibition or other means
- "P" document published prior to the international filing date but later than the priority date claimed
- "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
- "X" document of particular relevance: the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
- "Y" document of particular relevance: the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
- "&" document member of the same patent family

Date of the actual completion of the international search 24 January 1994	Date of mailing of the international search report 04 -02- 1994
Name and mailing address of the ISA/ Swedish Patent Office Box 5055, S-102 42 STOCKHOLM Facsimile No. + 46 8 666 02 86	Authorized officer Magnus Westöö Telephone No. + 46 8 782 25 00

INTERNATIONAL SEARCH REPORT
Information on patent family members

30/12/93

International application No.
PCT/SE 93/00946

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
DE-C1- 911293	17/09/53	NONE	